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TANTALUM ALLOY CHEMICAL VAPOR PLATING OF GUN BARRELS

CHEMETAL CORPORATION

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TANTALUM ALLOY CHEMICAL VAPOR PLATING OF GUN BARRELS

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NOVEMBER 1975

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A CVD technique for alloy deposition on gun barrels was successfully demonstrated and explored. The specific system employed the generation of mixed tantalum tungsten chloride species from a single generator containing Ta-10W alloy chips reacted with flowing chlorine gas. This mixture was then mixed with hydrogen and the total mixture passed through a heated gun barrel where deposition took place. The barrel materials used were Vascojet MA and Inconel 718. Formation of a more uniform, finer, grain structure with a lower microhardness than

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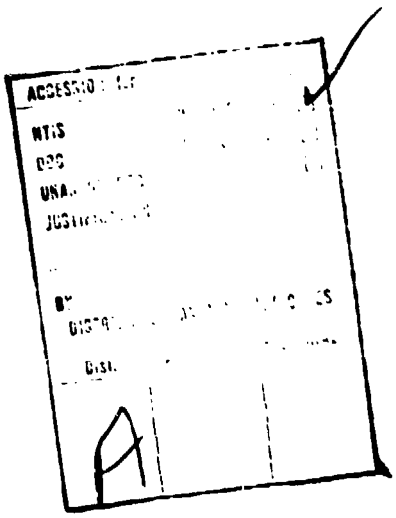
previously reported for CVD deposition was achieved.

Reasonably good uniformity was achieved with regard to composition over the full length of the particular barrel geometry. Typical variations in tungsten composition were between 8% and 12% by weight. Problem areas encountered were deposition thickness, end effects, and non-concentricity. Subsequent studies to eliminate the problems encountered and effect a suitable technique for Ta-10W alloy deposition on gun barrel bores are recommended. (Glaski, F. A. and Crowson, A.)



FOREWORD

This report was prepared by Dr. Fred A. Glaski of Chemetal Corporation, San Fernanado Laboratories Division, Pacoima, California and Dr. Andrew Crowson of the Research Directorate, GEN Thomas J. Rodman Laboratory, Rock Island Arsenal.

The report covers work performed by Chemetal Corporation under contract DAAF03-73-C-0144. Evaluation of the delivered coated barrels was performed at Rock Island Arsenal. This work was authorized as part of the Manufacturing Methods and Technology Program of the U.S. Army Materiel Command and was administered by the U.S. Army Production Equipment Agency.

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INTRODUCTION

Previous publications[1,2,3] have described in detail the mechanism of gun bore erosion and eventual failure. During firing of a large number of rounds of ammunition, combustion of the predominately nitrocellulose propellants produces end products of a reducing nature. Deterioration of the substrate under the high temperatures and pressures encountered during firing produces erosion of the gun barrel. As a result of the material erosion in the bore, propellant combustion gases escape between the projectile and the bore surface. This gas blowby further increases projectile and barrel erosion and transports eroded particles along the bore where they are redeposited. This action can lead to a decrease in the projectile muzzle velocity, reduction in firing accuracy, and reduces the effective range of the gun.

Chromium electrolytic plating remains the most economical method to provide a wear resistant and thermal barrier against the severe conditions encountered within the gun tube. However, the porosity and inherent crack network found in the chrome plate often leads to shearing and flaking in the early rounds of firing.[4] Also, progressive softening of plate occurs with firing, thereby decreasing the wear resistance. For these reasons, efforts were made to select or develop materials which would provide increased gun tube service lives relative to chromium plated steel.

In examining the physical and mechanical properties of available materials, the selection process turns to refractory metals or alloys. On the basis of mechanical properties, alloys of tantalum appear to be ideal choices. Previous efforts with co-extruded 7.62mm gun tubes with Ta-10W liners have been quite successful.[5] However, the high cost of the co-extrusion process served as an impetus to search for more economical methods to provide such refractory alloy surfaces on the ID of gun tubes. As a natural course, the search led to the examination of various coating processes to apply such materials.

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[1] Meyer, K. H. and Gehring, J. W., "A New Technique for Retarding Erosion in the Bores of Gun Barrels," AFATL-TR-76-24, February 1970.

[2] Taylor, D. J. and Morris J., "Gun Erosion and Methods of Control," Proceedings of the Interservice Technical Meeting on Gun Tube Erosion and Control, February 1970.

[3] Ebihara, W. T., "Investigation of Erosion in 7.62mm Machine Gun Barrels," Proceedings of the Interservice Technical Meeting on Gun Tube Erosion and Control, February 1970.

[4] Meyer, K. H., "Study of New Barrel Materials," AFATL-TR-70-79, August 1970.

[5] Tooke, R. C., and DiBenedetto, J. D., "A Study of the Diffusion Zone Between Ta-10W Alloy and 4150 Steel," R-RR-T-1-76-73, October 1973.

Since an alloy of Ta-10W cannot be suitably plated by conventional methods, the chemical vapor deposition (CVD) process is utilized. Like electroplating and physical vapor deposition, CVD is an atomistic process in that the deposit is built up atom by atom.[6] It is, therefore, capable of producing deposits of maximum density and of closely reproducing fine details in the substrate. Unlike other processes, it is a most versatile and flexible means of applying impervious metallic or ceramic coatings on a variety of substrate materials at temperatures far below the melting point of the resultant coating.

Chemical vapor deposition consists essentially of reducing or thermally decomposing, in its vapor or gaseous state, a volatile compound of the specified coating material upon a heated surface. Deposition can be effected in a variety of ways, such as: (1) hydrogen reduction reactions, generally of a metal halide, (2) metal reduction reactions, generally magnesium reduction of a metal halide or (3) thermal decomposition reactions, generally the thermal deposition of a metal halide or of an organometallic compound. In the case of the refractory metals, tungsten and tantalum, the preferred method is the hydrogen reduction of their corresponding chlorides.

In order to successfully plate alloys of refractory metals, an experimental matrix involving all processing parameters for the chemical vapor deposition process must be established. Included in these are: (1) deposition temperature, (2) total system pressure, (3) reactant gas phase concentrations (4) rate of supply of plating gases to surface and (5) rate of removal of gaseous products. Coating thickness, quality of coating, alloy composition and coating-substrate interface will be influenced in all cases by the aforementioned variables.

The objective of this project was to evaluate chemical vapor deposition as a process for applying bonded, uniform coating of tantalum/tungsten alloy (desirably 10% tungsten) on M134 gun barrels. The M134 gun barrels were 22" long by 7.62mm ID-rifled. The gun barrel materials were Vascojet MA and Inconel 718. Evaluation of the influence of CVD processing parameters on the quality and integrity of the coating were also to be determined.

EXPERIMENTAL PROCEDURE

A schematic diagram of the apparatus designed and used for vapor plating of Ta-10W on gun barrel bores is shown in Figure 1. Basically, it consisted of a 1 1/2" diameter x 28" long Inconel 600 retort flanged at both ends. The specific system employed the direct chlorination of a heated bed of Ta-10W chips. The mixed chlorides generated in the chlorinator were combined with hydrogen gas and the total gas mixture was flowed through the gas inlet end. The total mixture was directed through the barrel through positive containment measures where deposition was effected on the interior surface of the heated barrel. The residual reactant gases and product

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[6] Powell, C. F., Oxley, J. H. and Blocher, J. M., Vapor Deposition, John Wiley and Sons, Inc., pp 250, 1966.

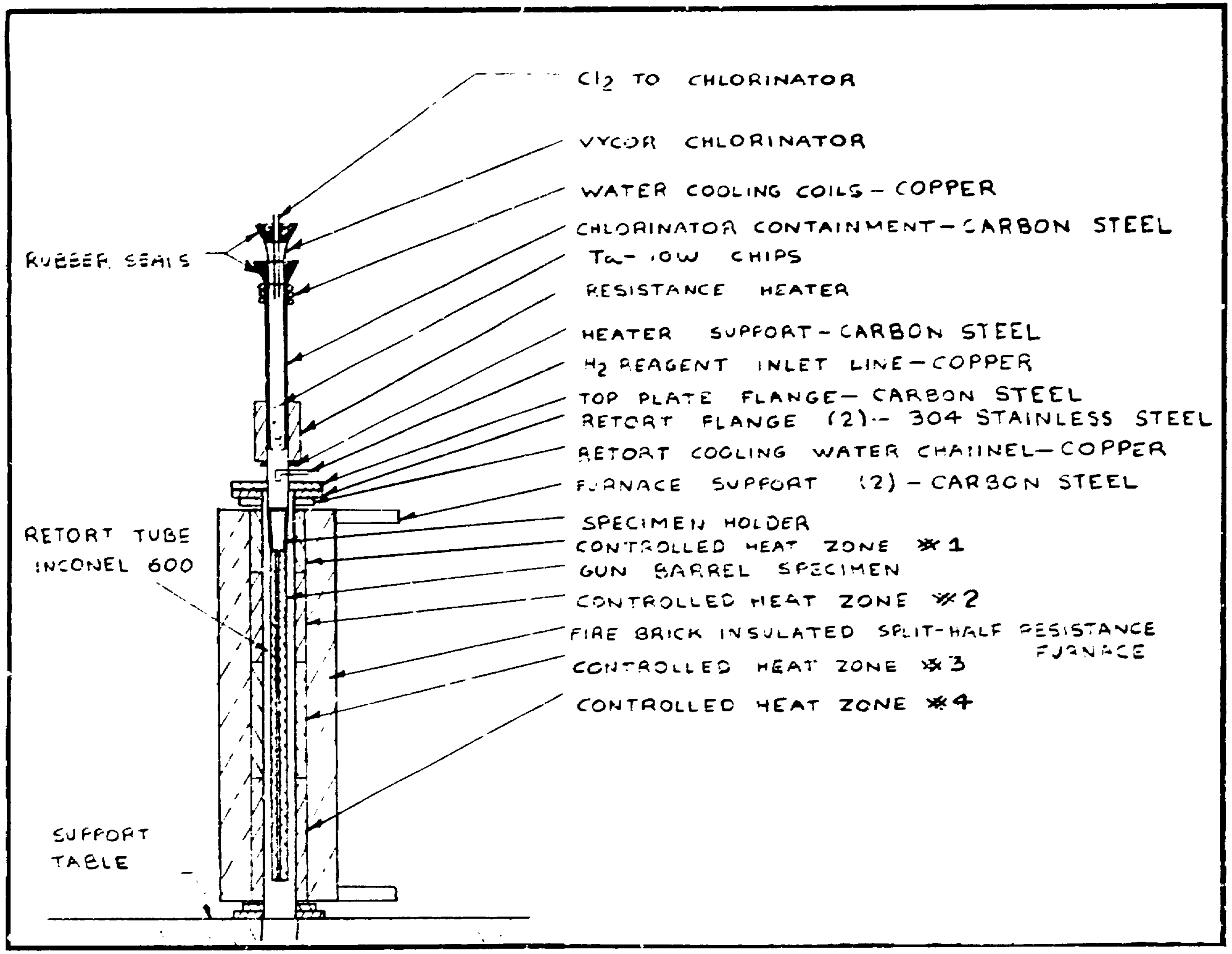


FIGURE 1 Schematic Diagram of Apparatus Designed and Used for 22" Long X 7.62mm. Gun Barrel Deposition

gases flowed from the exhaust end of the barrel into the vacuum system below the retort. The retort was heated over the entire length of the barrel by four separately controlled nichrome resistance heaters which were of the clamshell variety to permit the rapid simultaneous removal of all four heaters from the retort at the conclusion of the deposition run. This feature was thought to be quite important to the design of the overall equipment because the rapid cooldown or "quench" was necessary to permit proper post-CVD heat treatment to restore the mechanical properties of the steel. The system was capable of operating at temperatures above 1200°C.

The basic chemical reactions for these steps were:

Chlorination:

$$2Ta(s) + 5Cl_2(g) \xrightarrow{850^oC} 2TaCl_5(g) \qquad (1)$$

$$W(s) + 3Cl_2(g) \xrightarrow{1000^oC} WCl_6(g) \qquad (2)$$

Deposition:

$$2TaCl_5(g) + 5H_2(g) \xrightarrow{1050^oC} 2Ta(s) + 10HCl(g) \qquad (3)$$

$$WCl_6(g) + 3H_2(g) \xrightarrow{1050^oC} W(s) + 6HCl(g) \qquad (4)$$

The key in the alloy coating process was to obtain a proper balance to achieve uniformity with regard to composition as well as coating thickness. Total gas flow and pressure were found to be the most important parameters in controlling thickness uniformity, which was, in fact, a function of the velocity of the gases and reactant gas preheat. The compositional uniformity was generally achieved by adjusting the hydrogen mixture ratio and the temperature of the steel substrate. It would have been also possible to exercise control over both compositional and thickness uniformity by employing a temperature gradient over the length of the barrel; however, because of the temperature sensitive structure of the steel, the same isothermal conditions should be employed throughout the process.

RESULTS AND DISCUSSION

Deposition Studies

Parametric studies were initially conducted on the exterior surface of molybdenum rod mandrels. Table 1 summarizes deposition runs which typified results obtained. Depositions conducted at 1200°C, 1100°C and 1000°C produced corresponding decreases in tungsten content from 9 w/o to 3 w/o; all depositions taking place at 30 torr pressure. Later, the pressure was increased stepwise to 150 torr in an effort to increase the tungsten content at 1000°C. Microhardness data indicated a corresponding increase in tungsten content with increasing pressure. Alloys of 3 w/o up to 16 w/o tungsten were obtained under these studies.

Metallography of various deposits obtained on the exterior surfaces

TABLE 1

SUMMARY OF EXTERIOR DEPOSITIONS

RUN NO.	1*	2	3	4	5	6	7
Deposition Temp., °C	1200	1100	1000	1000	1000	1000	950
Chlorinator Temp., °C	1000	1000	1000	1000	1000	1000	1000
Pressure, Torr	28-30	26-28	26	62-66	150	100	150
H_2 flow, std. cc./min.	2150	2150	2150	2150	2150	2150	2150
Cl_2 flow, std. cc./min.	1050	1050	1050	1050	1050	1050	1050
Deposition time, min.	45	45	45	60	60	90	90
Plate thickness, in.	0.015"	0.012"	0.011"	---	0.007"	0.012"	0.005"
Microhardness, VHN	245	185	150	160	500	235	250
w/o W, via electron microprobe	8.5	5.5	3	3	16	4.5	1.5

*Shown in Figure 1

are shown in Figures 2 and 3. Deposits obtained from the chlorinated Ta-10W alloy (see Figure 2) were found to be of a finer grain than deposits previously made from separate tantalum and tungsten chlorinated sources (see Figure 3).

Immediately following the exterior studies, interior deposition studies using 6" long X 0.3" ID 4130 steel specimens were undertaken. The parametric studies conducted in the exterior depositions were essentially repeated initially and adjusted appropriately to compensate for the difference between the ID and the OD application. Significant deviations from OD data were observed. The effect of pressure on tungsten composition, for example, appeared to become less prominent than originally thought. In ID depositions below 1000°C, gas preheat became most important to maintain deposition rate. Also "cold wall" effects influenced tungsten deposition more than tantalum deposition since WCl_6 was less volatile than $TaCl_5$ and the former chloride condensed more readily on cooler surfaces; and this directly affected deposition composition in OD runs. This was a helpful development because pressure then could be varied to control deposit thickness uniformity on 22" long barrels with little effect upon alloy composition. It was planned at this point that 22" long specimens would be coated with Ta-W alloy using pressure and inert gas diluent to vary gas velocity and thereby control thickness uniformity. Likewise, temperature and gas mixture ratio variations were to be employed to control alloy composition.

All of the parametric studies for interior depositions were conducted on 22" long X 0.3" ID 4130 steel mandrels. Tables 2 and 3 summarizes key deposition runs which were obtained. Figures 4 to 9 show the relative microstructure of Ta-W alloys ranging from 3% W to 53% W accomplished in these studies. In the case of the 4130 steel deposition study, chromium plated steel mandrels was the only source material provided. The results of the parametric study showed consistency with the short tube deposition studies. The most profound effect on compositional uniformity was hydrogen mixture ratio and temperature. A lowering of the hydrogen content resulted in decreases in tantalum composition.

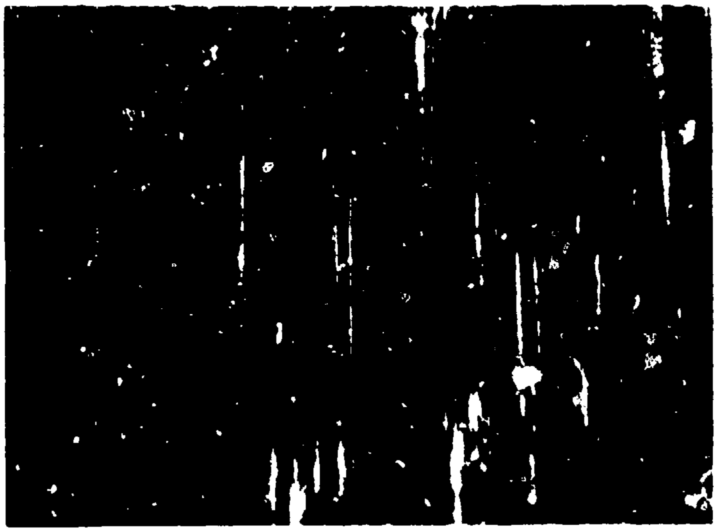
Total gas flow and pressure had the predominate effect on thickness; low pressure was required to effect a high velocity, low residence time and minimal gas preheat. In this manner, good uniformity between 0.002" and 0.003" coating thickness was achievable on a 22" long specimen.

Ta-10W Coating in Rifled Barrels

The deposition condition parameter specifications developed on trial mandrels were readily translated to rifled barrels. The size of the barrels was 22" long by 7.62mm in diameter. The gun tube materials were Vascojet MA and Inconel 718. Table 4 gives the deposition conditions for the Ta-W coated gun barrels.

One of the most significant problems encountered in the plating process was bonding. A reasonably well bonded system on both Vascojet MA and Inconel 718 (see Figures 10 and 11) was produced with exception of the end effect (see Figures 12 and 13). A photograph of a sectioned barrel showing the muzzle, center and breech sections is shown in Figure 14 for comparison. The gun barrels repeatedly developed low spots in thickness at

FIGURE 2



Ta-8.5%W Alloy Deposited from Chlorinated Ta-10W Alloy at 1200°C on Mo Rod Substrate (400x)

FIGURE 3

Ta-10W Alloy Deposited from Separately Chlorinated Ta-W (100x)

TABLE 2

PARAMETER SUMMARY OF KEY INTERIOR TRIAL DEPOSITIONS

(Substrate: 22" long x 0.3" I.D. 4130 Steel Tubes)

RUN NO.	2	3	4	5	6	9	11	24*	35	50
Deposition Temp., °C	1040	1040	1000	1040	1040	1040	1040	1040	1040	1040
Chlorination Temp., °C	980	980	980	980	980	980	980	980	980	980
Pressure, Torr	36	36	36	36	28	36	36	36	20	20
Ar flow, std. cc./min.	400	500	500	530	500	500	-0-	500	500	500
H_2 flow, std, cc./min.	270	270	270	135	270	540	810	200	200	200
Cl_2 flow, std. cc./min.	135	135	135	135	135	135	135	135	135	135
Deposition time, hr.	3	3	3	3	3	3	3	2	1-1/2	2

* 26" long specimen

TABLE 3

UNIFORMITY PROFILE SUMMARY OF KEY INTERIOR TRIAL DEPOSITIONS

(Substrate: 22" long x 0.3" I.D. 4130 steel tubes)

RUN NO. 2 Data Point	TEMPERATURE (C^{o})	PLATE THICKNESS (Mils)	HARDNESS (VHN)	COMPOSITION (w/o W)
1	----	3.5	570	30
2	----	8	350	11
3	----	4	350	8
4	----	4	290	5
5	----	4	260	3
6	----	2	550	5
RUN NO. 3				
1	900	8	480	24
2	----	7	340	13
3	1040	3	395	9
4	1040	2.5	350	6
5	----	3.5	270	5
6	1040	1.5	435	6
RUN NO. 4				
1	1000	1.5	1500	50
2	----	2.5	700	23
3	1000	3	700	12
4	995	2.5	500	6
5	----	2.5	340	7
6	1000	1.25	625	10
RUN NO. 5				
1	1045	2	1715	54
2	----	5	510	23
3	----	4.5	510	17
4	1045	2,5	390	14
5	----	2.5	560	11
6	1045	1.25	745	13
RUN NO. 6				
1	1045	1.5	1130	46
2	----	7	350	18
3	----	5.5	310	11
4	1045	4.5	310	8
5	----	4	290	6
6	1040	2	580	6

T A B L E 3 (cont'd.)

RUN NO. 9 Data Point	TEMPERATURE (C^o)	PLATE THICKNESS (Mils)	HARDNESS (VHN)	COMPOSITION (w/o W)
1	1040	1.5	650	27
2	----	5.5	380	9
3	1040	4.5	315	5
4	1040	4.5	220	3
5	----	6.5	205	2
6	1040	3.5	340	2
RUN NO. 11				
1	1040	1	750	--
2	----	9.5	300	10
3	1040	5.5	225	4
4	1040	6.5	232	1
5	----	8	180	1
6	1040	2.5	320	11
RUN NO. 24				
1	1040	2.5	465	22
2	----	2	325	12
3	1040	1.5	350	9
4	1045	1.5	350	9
5	----	2	300	8
6	990	2	360	8
7	----	1.5	345	9
RUN NO. 35				
1	1040	1.5	860	53
2	----	2	390	25
3	1040	1.5	390	15
4	1040	1	415	12
5	----	1.5	425	10
6	965	2	175	7
RUN NO. 50				
1	1040	4.5	750	20
2	----	7	355	10
3	1040	3	355	10
4	1040	2.5	340	5
5	----	6	260	4
6	980	4	255	3

FIGURE 4 Ta-3W on 4130 Steel, Run 9-4 (435x)

FIGURE 5 Ta-10W on Cr-Plated Steel, Run 35-5 (435x)

FIGURE 6 Ta-15W on Cr-Plated Steel, Run 35-3 (435x)

FIGURE 7 Ta-20W on Inconel 718, Run 19 (200x)

FIGURE 8 Ta-25W on Cr-Plated Steel, Run 35-2 (435x)

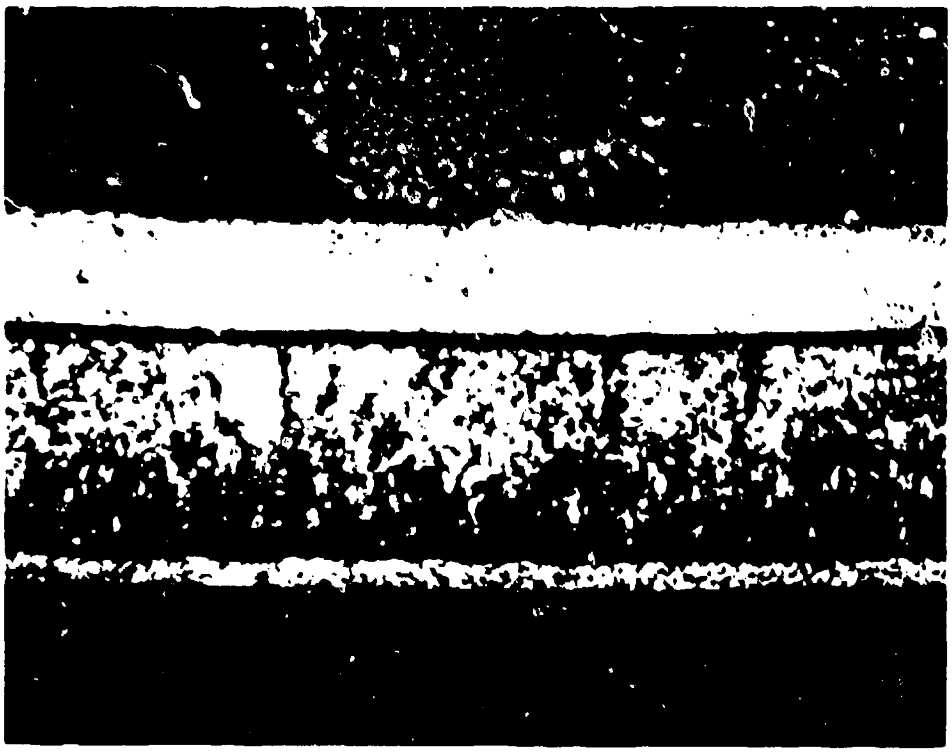


FIGURE 9 Ta-53W on Cr-Plated Steel, Run 35-1 (435x)

TABLE 4

DEPOSITION CONDITIONS FOR Ta-W COATED DELIVERED BARRELS

	Vascojet MA	Inconel 718
Titanizing Temp. °C	1095	N.A.
Titanizing Time, min.	30	N.A.
Titan. Ar flow, std. cc/min.	500	N.A.
Titan. H_2 flow thru $TiCl_4$ std. cc/min.	540	N.A.
Pressure, torr.	36	N.A.
CVD Ta-W Temp °C	1040	1040
Chlorinator Temp. °C	980	980
Deposition time, min.	120	120
Ar flow, std. cc/min.	500	500
H_2 flow, std. cc/min.	540	540
Cl_2 flow, std. cc/min.	135	135
Pressure, torr.	20	20
Post-deposition H.T. temp. °C	N.A.	1110
Time of H.T., min.	N.A.	15
"Quench" time to below red heat, min	1	1

Ta-W

Vascojet MA

FIGURE 10 Ta-10W on Vascojet MA, 15" from Muzzle (200x)

FIGURE 11   Ta-10W on Inconel, 15" from Muzzle (200x)

FIGURE 12   Ta-W on Vascojet MA, 6" from Muzzle (200x)

Ta-W

Inconel

FIGURE 13 Ta-10W on Inconel, 6" from Muzzle (200x)

Muzzle

Center

Breech

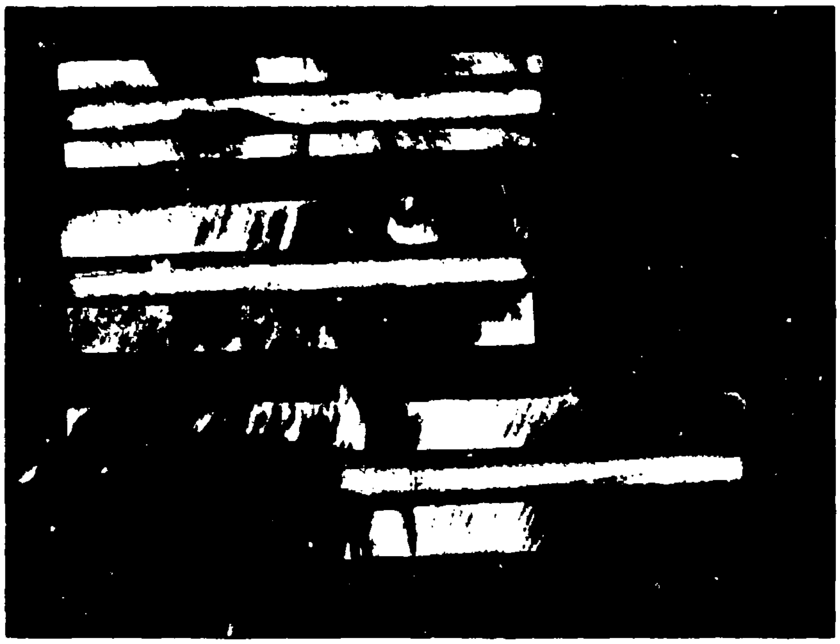


FIGURE 14 Sectioned Gun Barrel Coated with Ta-10W

the extreme inlets and outlets and this corresponded to an increase in tungsten composition at these points. To overcome the low spots, the deposition parameters were adjusted - the hydrogen-argon mixture ratio increased slightly, the pressure decreased, and the temperature decreased slightly to lower the tungsten composition at the inlet end of the barrel. This in turn lowered the tungsten content over the remaining length of the barrel. Despite repeated efforts, the low spots still occurred at the end of the barrel in all cases.

Thickness uniformity of the barrels was another area in which problems occurred. Table 5 gives air gauge measurements taken on the barrels. Specifications of gun barrels designate that the breech end diameter to be 0.3000 + 0.0015" after plating (0.2995" minimum) with muzzle end never exceeding breech end with minimum diameter of 0.295". Elucidation of the measurements shows nonuniformity of the coating down the barrel.

A better understanding on how the coating thickness varied for the respective barrel is shown in Table 6. Two barrels chosen at random, one Vascojet MA and the other, Inconel 718, were sectioned and analyzed. Overall, the Ta-10W coatings were found to be well below the required plating thickness range of 2.0 ± 0.10 mil). In both cases, the coating thickness was found to increase at the ends of the barrel and decrease towards the center significantly.

Concentricity measurements (see Table 7) were determined to evaluate warpage of the gun barrels after the CVD exposure and subsequent heat-treatment. Heat treatment was accomplished in the following manner: The Vascojet was cooled from 1050°C deposition temperature to below red heat within sixty seconds and the Inconel 718 was cooled at the same rate after a 15 minute soak at 1100°C.

Gun barrel specifications require that for the length of the barrel, the diameter of the muzzle end shall be concentric with the center line of the barrel within 0.006" TIR (total indicated run out) regardless of the feature size. Also, the four elements of the muzzle end shall be concentric with each other within 0.002" TIR at maximum material condition. The Inconel 718 barrels were found to be slightly non-concentric with respect to the requirements. Extreme warpage of Vascojet MA barrels was noted from the measurements. In all cases, Inconel 718 and Vascojet MA, non-concentricity to some extent was found towards the muzzle end of the barrel.

CONCLUSIONS AND RECOMMENDATIONS

This program showed that the basic Ta-10W CVD system for coatings on ID gun tube surfaces is definitely in the realm of feasibility. The bonding of the alloy was primarily limited by the end effects of the Vascojet and Inconel barrels. Such conditions were improved when the length of the retort and heater clamshell apparatus was increased by 4 inches and 26 inches long trial mandrels of 4130 steel used. Under these conditions, bonding at the 22 inch point, or 2 inches in from each end, was found comparable to the rest of the tube.

TABLE 5

AIR GAUGE MEASUREMENT OF ID LAND

BARREL NUMBER

DISTANCE FROM MUZZLE END	74-2-4	74-2-5	74-2-6	74-2-7	74-2-8	74-2-9	74-2-10	74-2-11	74-2-12	74-2-13
1"	0.3075	0.3016	0.2960	0.2975	0.2981	0.2977	0.3069	0.2958	0.3040	0.3032
2"	0.3075	0.3014	------	------	0.2995	------	0.3075	------	0.3026	0.3034
3"	0.3075	0.3008	------	------	0.2991	0.3018	0.3070	0.2958	0.3021	0.3031
4"	0.3066	0.3024	------	------	0.2999	0.3022	0.3071	------	0.3020	0.3034
5"	0.3062	0.3025	------	0.2965	0.3004	0.3030	0.3074	0.3017	0.3031	0.3034
6"	0.3064	0.3033	------	0.2988	0.3004	0.3034	0.3071	0.3018	0.3038	0.3034
7"	0.3066	0.3038	------	0.3000	0.2995	0.3032	0.3071	0.3030	0.3043	0.3034
8"	0.3074	0.3039	------	0.3004	0.3004	0.3039	0.3074	0.3007	0.3044	0.3034
9"	0.3068	0.3041	------	0.3000	0.3004	0.3038	0.3074	0.3034	0.3045	0.3035
10"	0.3069	0.3044	------	0.2995	------	0.3043	0.3074	0.3033	0.3045	0.3037
11"	0.3070	0.3044	------	0.2999	------	0.3042	0.3075	0.3040	0.3045	0.3035
12"	0.3072	0.3045	------	0.2997	------	0.3045	0.3074	0.3039	0.3044	0.3034
13"	0.3069	0.3044	------	0.2998	------	0.3044	0.3074	0.3037	0.3045	0.3034
14"	0.3068	0.304[illegible]	------	0.2994	------	0.3044	0.3074	0.3037	0.3043	0.3034
15"	0.3068	0.304[illegible]	------	0.3000	------	0.3041	0.3070	0.3032	0.3040	0.3035
16"	0.3067	0.3043	------	0.3000	------	0.3044	0.3074	0.3032	0.3041	0.3034
17"	0.3065	0.3040	------	0.2998	------	0.3041	0.3071	0.3030	0.3040	0.3034
18"	0.3064	0.3038	------	0.2997	------	0.3041	0.3074	0.3038	0.3041	0.3034
19"	0.3065	0.3029	------	0.2996	------	0.3037	0.3074	0.3036	0.3037	0.3034
20"	0.3067	0.3023	0.3040	0.2983	0.3025	0.3029	0.3075	0.3034	0.3038	0.3036

NOTE: All unreported values in above table, unavailable due to non-concentricity of barrel.

TABLE 6

GUN BARREL COATING THICKNESS MEASUREMENTS

Distance from muzzle (in)	Barrel 74-2-8 (mils)	Barrel 74-2-12 (mils)
3	3.1	2.8
6	1.6	1.4
9	1.4	1.0
12	1.0	1.0
15	1.2	1.6
18	2.0	1.8

NOTE: 1. Barrel 74-2-8 is Vascojet MA

2. Barrel 74-2-12 is Inconel 718

TABLE 7

CONCENTRICITY MEASUREMENTS OF GUN BARRELS

BARREL NO.	SUBSTRATE	CONCENTRIC POINTS ON BARREL 1	2	3	4
74-2-4	(1718)	0.003	0.004	0.008	0.012
74-2-5	(1718)	0.002	0.004	0.006	0.009
74-2-6	(V-MA)	0.007	0.017	0.024	0.016
74-2-7	(V-MA)	0.019	0.053	0.082	0.084
74-2-9	(1718)	0.002	0.004	0.005	0.009
74-2-10	(1718)	0.005	0.009	0.012	0.015
74-2-11	(V-MA)	0.018	0.050	0.078	0.090

Other major problems encountered in the program re thickness uniformity and non-concentricity. Adjustment of present parameters (pressure and inert gas diluent) needs to be evaluated in future depositions to eliminate the problem of thickness uniformity. In the case of non-concentricity, post heat treatment of the coated barrel is desirable to prevent the occurrence of the warpage found in the muzzle ends. Further evaluations regarding optimum coating-substrate material system, and coating thickness should be performed.

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